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Thermal Radiation from Large Pool Fires

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Preface

This report was developed to be used specifically in implementing the technical requirements of 24 CFR Part 51, Subpart C of the Code of Federal Regulations, entitled, *Siting of HUD-Assisted Projects Near Hazardous Operations Handling Conventional Fuels or Chemicals of an Explosive or Flammable Nature.* The material contained in this report is for the use of the Department of Housing and Urban Development (HUD) staff or any other individual, organization or agency considering the location of HUD-assisted projects near materials of an explosive or flammable nature. It contains the theoretical development plus the step by step procedures for determining the Acceptable Separation Distance (ASD) for a HUD-assisted project from a specific hazard source. The acceptable separation distance standards are found in the HUD Regulation at 24 CFR Part 51, Subpart C (paragraph 51.203).

This report addresses primarily the ASD requirements for thermal radiation. Prior to this work, a calculation procedures for determining ASD was set forth in a 1982 HUD Guidebook entitled, *Urban Development Siting with Respect to Hazardous Commercial/Industrial Facilities* [1]. Much of the theoretical development for the 1982 guidebook is contained in a 1975 HUD Guidebook entitled *Safety considerations in siting housing projects* [2]. In the quarter century since these reports were released, the field of fire science has grown rapidly, leading to improved methods of measurement and prediction of fire behavior. A review by the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST) of the 1975 HUD guidelines for thermal radiation flux has revealed that for certain fire scenarios the methodology can produce estimates of radiation flux that are up to an order of magnitude larger than those actually measured in field experiments. The principal reason for this discrepancy is the assumption that large fires are unobscured by smoke, that is, a person watching the fire from a distance sees the entire extent of the combustion region. In reality, large fires of most combustible liquids and gases generate an appreciable amount of smoke that shields much of the thermal radiation from striking nearby structures or people.

In this report, a new methodology for computing thermal radiation flux from large fires of combustible liquids and gases is put forth. The methodology is similar to that described in the 1975 HUD guidelines, but contains improved estimates of fire size and radiant intensity.

Contents

1 Introduction

Industrial fires can be intense emitters of heat, smoke, and other combustion products. This is particularly true if the fuel is a petroleum based substance, with a high heat of combustion and sooting potential. The radiant energy flux can be sufficiently high to threaten both the structural integrity of neighboring buildings, and the physical safety of fire fighters, plant personnel, and potentially people beyond the boundaries of the facility.

The Department of Housing and Urban Development (HUD) has established thermal radiation flux levels of 31.5 kW/m^2 (10,000 Btu/h/ft^2) for buildings and 1.4 kW/m^2 (450 Btu/h/ft^2) for people as guides in determining an "Acceptable Separation Distance" (ASD) between a fire consuming combustible liquids or gases and nearby structures and people (24 CFR Part 51, Subpart C (paragraph 51.203)). The calculation procedure for determining ASD is set forth in a 1982 HUD Guidebook entitled, *Urban Development Siting with Respect to Hazardous Commercial/Industrial Facilities* [1]. Much of the theoretical development for this guidebook is contained in a 1975 HUD guidebook entitled, *Safety considerations in siting housing projects* [2]. In the quarter century since that report was released, the field of fire science has grown rapidly, leading to improved methods of measurement and prediction of fire behavior. A review by the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST) of the 1975 HUD guidelines for thermal radiation flux has revealed that for certain fire scenarios the methodology can produce estimates of radiation flux that are up to an order of magnitude larger than those actually measured in field experiments. The source of this discrepancy is the assumption that the fire is unobscured by smoke, that is, a person watching the fire from a distance sees the entire extent of the combustion region. In reality, large fires of most combustible liquids and gases generate an appreciable amount of smoke. Depending on the fuel and the size of the fire, up to 20 % of the fuel mass is converted to smoke particulate in the combustion process [3]. This smoke shields much of the luminous flame region from the viewer, and it is this luminous flame region that is the source of most of the thermal radiation. This shielding effect is most pronounced for fires that are tens or hundreds of meters in diameter because of the decreased efficiency of combustion at these scales. A schematic diagram is shown in Fig. 1.

2 Literature Review

A number of references were reviewed during the preparation of this report, including those cited in the 1975 HUD guidelines [2]. An extensive summary of research in the area of thermal radiation from large fires is contained in the chapter in the Society of Fire Protection Engineers (SFPE) Handbook entitled, *Fire Hazard Calculations for Large Open Hydrocarbon Fires* [4]. A summary of various calculation methods is included in the SFPE Engineering Guide entitled, *Assessing Flame Radiation to External Targets from Pool Fires*, published in June, 1999 [3]. The methodology to be described in the present report is not dramatically different from those in the SFPE Engineering Guide. However, in order to maintain the simplicity of the original HUD methodology, it has been necessary to adopt a slightly different approach that emphasizes global energy conservation as a way of minimizing errors in radiation flux predictions due to uncertainties in the measurements upon which the flux calculations are based.

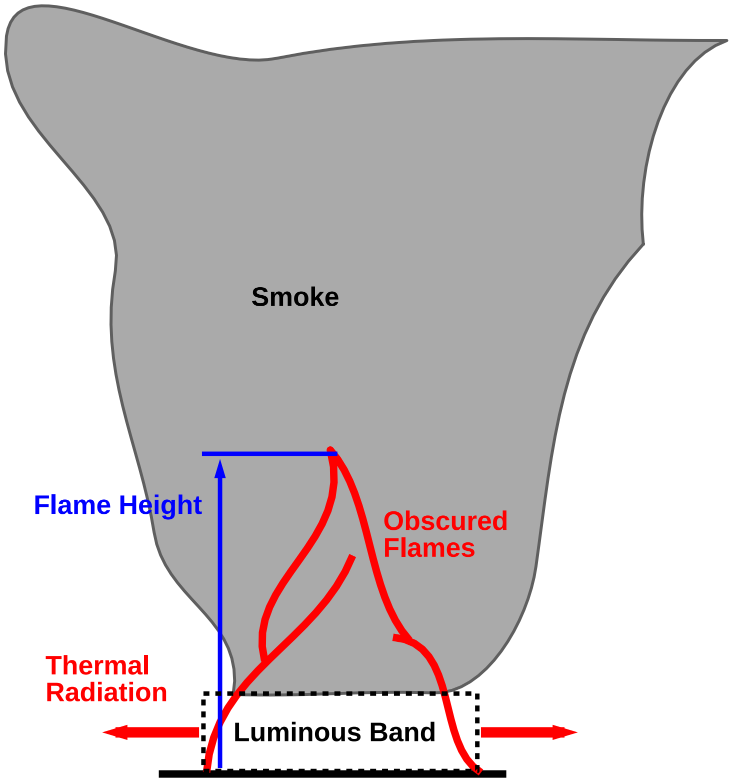

Figure 1: Schematic diagram of a large liquid fuel fire.

3 Theoretical Development

The goal of the analysis is to produce a methodology for estimating the thermal radiation flux from large fires burning either combustible liquids or gases. A partial listing of these combustible liquids and gases is given in Appendix I to Subpart C of 24 CFR Part 51, *Siting of HUD-Assisted Projects Near Hazardous Operations Handling Conventional Fuels or Chemicals of an Explosive or Flammable Nature*. A partial listing of hazardous liquids includes crude oil, diesel fuel, gasoline, jet fuel, kerosene and toluene. A partial listing of hazardous gases includes butane, hydrogen, LNG, LPG and propane. The analysis of hazardous liquid fires is relatively independent of the type of liquid; burning rates and heat release rates do not vary significantly from fuel to fuel, nor does the nature of the fire. However, hazardous gases stored under pressure, especially LNG and LPG, are not as predictable. There are a number of references to fires involving LPG and LNG in which a cloud of combustible gas ignited to form fireballs on the order of 100 m in diameter. The radiation from fires fueled by gases leaking from storage tanks can cause a BLEVE (Boiling Liquid Expanding Vapor Explosion) within a tank that not only produces a tremendous amount of thermal radiation, but also often causes parts of the tank to be thrown tens or hundreds of meters. In particular, LPG is so volatile that it is more likely to vaporize than form a liquid pool, thus much of the research into large liquid fuel fires may not be applicable to LPG fires.

Predicting the thermal radiative flux from a fire of leaking combustible gases is more complicated than that of a liquid fuel fire because there are a number of potential fire scenarios to consider. With a liquid fuel fire, the dynamics of the fire is more understood and predictable than with a gaseous fuel. Rather than develop a separate methodology for estimating thermal radia-

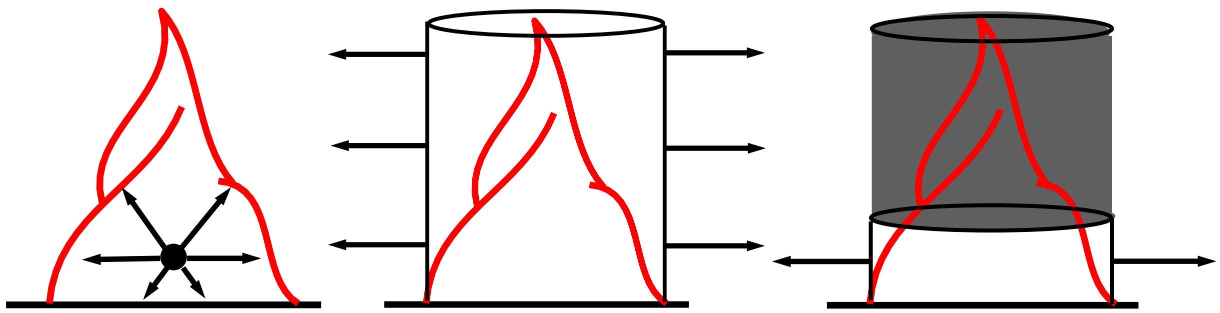

Figure 2: Schematic diagram of thermal radiation models.

tion for each potential gaseous fire scenario, it is preferable to employ a simple procedure which encompasses a wide variety of scenarios, removes most of the geometrical parameters from the calculation, and remains conservative. Such a method is known as the "point source" radiation model (see Fig. 2). All that it requires is an estimate of the total heat release rate of the fire, and the fraction of that energy that is emitted as thermal radiation. These data are available based on far-field radiometer measurements [4]. The point source method is accurate in the far-field, but is considered overly conservative within a few fire diameters because it assumes that all of the radiative energy from the fire is emitted at a single point rather than distributed over an idealized shape (usually a cone or cylinder) meant to represent the fire.

For liquid fuel fires, however, the point source model may be too conservative because these fires are more predictable and there is much more experimental data available to validate a more detailed model. A popular method of estimating radiation flux from large liquid pool fires is the "solid flame" radiation model (Fig 2). In this case, the fire is idealized as a solid vertical cylinder emitting thermal radiation from its sides. This model is relatively simple, but it does require estimates of the diameter and height of the cylinder, plus an estimate of the emissive power. Determining the height and width of the idealized cylinder is discussed in the next section.

3.1 Hazardous Liquids

In the solid flame radiation model, the thermal radiation flux, $\dot{q}''$, from a fire to a nearby object is given by the expression

$$\dot{q}'' = F\,\tau\,\varepsilon_f\,E_f \tag{1}$$

where F is a geometric view factor that defines the fraction of energy radiated by the fire that is intercepted by the receiving object; τ is the atmospheric transmissivity to thermal radiation, mainly a function of humidity and distance between the radiation source and the receiver; ε_f is the effective emissivity of the flame, generally expressed as $1-e^{-\kappa D}$ where κ is an attenuation coefficient and D is the width of the fire; and E_f is the total emissive power of the flame at the flame surface. For fires greater than a few meters in diameter, the effective emissivity of the flame can be taken as one. Also, to be on the conservative side, the transmissivity is taken as one. What remains to be computed are the view factor F and the emissive power of the flame E_f.

Measurement of the emissive power of large fires is difficult and subject to considerable uncertainty. Computation methods of the past, including the 1975 HUD guidelines [2], considered the view factor and the emissive power independently, which for some fire scenarios led to estimates of radiative emission from the fire in excess of the total energy of the fire. What was missing from these analyses was an overall accounting of energy. This problem has been remedied in the last few decades because it is now generally recognized by the field of fire protection engineering that a fire's total heat release rate (HRR) is the best measure of its potential to do harm. Moreover, the HRR of a fire is easier to estimate than its temperature or physical size because the HRR is proportional to its rate of fuel consumption, a quantity that is relatively easy to measure.

The Building and Fire Research Laboratory at NIST has performed on the order of 100 large scale fire experiments in the past two decades with a variety of combustible liquids and gases, and one of the more reliable measurements is that of the mass burning rate from which the fire's total heat release rate (HRR) can be estimated [5]. A fraction of the fire's total HRR is emitted in the form of thermal radiation. For fires up to roughly four meters in diameter, the ratio of the rate of energy radiated to the surroundings to the total HRR of the fire, χ_r, is between 0.30 and 0.40, and this value decreases with increasing fire diameter due to smoke obscuration [4, 6, 3]. Much of the thermal radiation from a large, sooty fire is emitted from the luminous "wall" of flame encircling the base of the fire. The flames above this luminous wall are obscured from view by the smoke formed due to incomplete combustion. Air is entrained into the fire at its base, and soot quickly forms in the combustion process, creating a thermal barrier higher up in the fire that traps radiant energy from escaping the fire's interior.

An idealized picture of a fire used in most analyses of thermal radiation is one in which the fire is assumed to be cylindrical in shape with a height H and diameter D with a total HRR of $\dot{Q}$. More generally, the fire can be assumed to be of arbitrary shape with a perimeter length P. The radiated energy from the fire can be expressed as

$$\chi_r \, \dot{Q} = P \, H \, E_f \tag{2}$$

Radiometer measurements from large fire experiments [7, 6] suggest that χ_r decreases with increasing fire diameter D according to

$$\chi_r = \chi_{r_{\max}} \, e^{-kD} \tag{3}$$

where $\chi_{r_{\max}} = 0.35$ and $k = 0.05$ m^{-1}. These values are based on a curve fit to experimental data involving a range of different combustible liquids. Figure 3 displays the data along with the curve fit. The total HRR of the fire, $\dot{Q}$, can be expressed as the product of the heat release rate per unit area $\dot{q}''_f$ and the area of the base of the fire A

$$\dot{Q} = \dot{q}''_f \, A \tag{4}$$

For a given fuel, the heat release rate per unit area $\dot{q}''_f$ is relatively constant because the fuel mass burning rate per unit area is relatively constant [5].

The two remaining parameters in Eq. 2 are the emissive power E_f and the height H of the idealized cylinder. The reported values of the emissive power for flammable liquids and gases vary widely from source to source [4]. The variation in reported values of emissive power has to do with the definition of the height of the idealized cylinder that represents the fire. When viewed from a distance, the actual fire appears smokey, with occasional bursts of luminous flame emerging from the smoke. The flame height of the actual fire is defined as the vertical extent of the

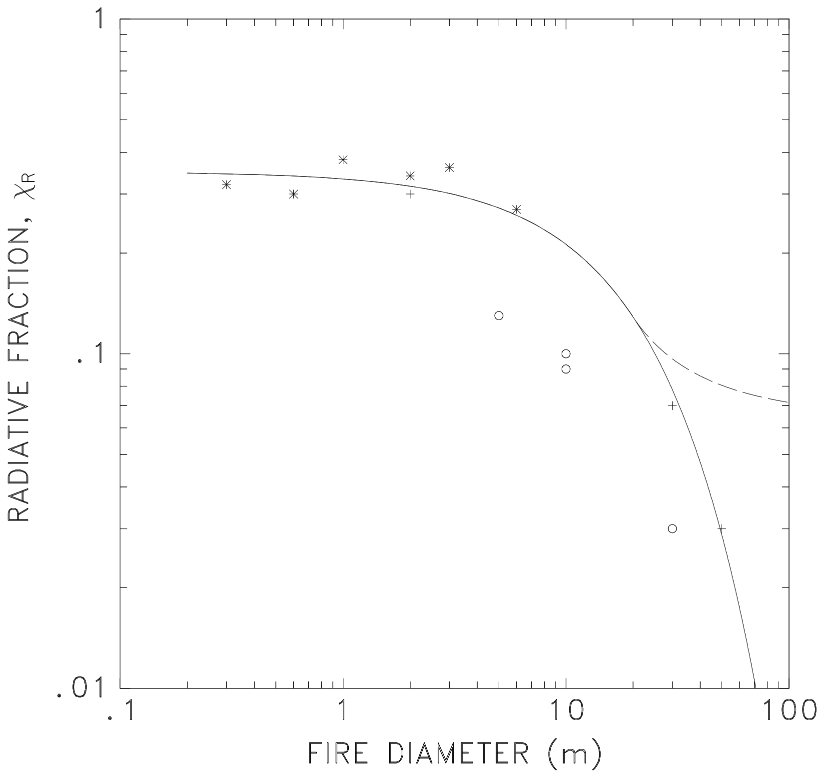

Figure 3: Radiative fraction, χ_r, as a function of fire diameter D for heptane (*), crude oil (○), and kerosene (+). The solid line is a curve fit $\chi_r = 0.35\,\exp(-kD)$ where $k = 0.05$ (see Eq. 3).

combustion region (see Fig. 1), and it can be thought of as the maximum height above the ground at which these luminous bursts can be seen. Taking an idealized cylindrical fire with height equal to the flame height of the actual fire (see Fig. 2), on average about 20 % of the surface area of the cylindrical fire consists of visible flames and 80 % is smoke [4]. Most of the visible flame is at the base of the fire, although periodically luminous flames burst through the smokey plume higher up. Figure 4 shows a photograph of a diesel fuel fire in a 15 m square steel pan. The reported values of emissive power are most often average values for the entire flame height, and will be significantly less than the emissive power of the luminous flames. If the relatively low average emissive power is applied to the surface area of the idealized cylinder whose height is equal to the flame height of the actual fire, then the estimate of the radiative flux at distances greater than a few fire diameters away will be accurate. However, at closer distances the radiative flux estimates will typically be under-estimated because the radiant energy is assumed to be distributed over the entire height of the fire, rather than concentrated near the base as it is in reality (see Fig. 2).

For example, for fires larger than 30 m in diameter, the average emissive power reported by many researchers is less than 31.5 kW/m^2 (10,000 Btu/h/ft^2) [4], the threshold value used by HUD for determining the Acceptable Separation Distance (ASD) for buildings and combustible structures. Figures 5–7 show empirical correlations of emissive power, E_f, and flame height, H, for two of the most widely used methods of predicting thermal radiation from large fires compared with the correlation developed here [3]. Both the method of Shokri and Beyler and the method of

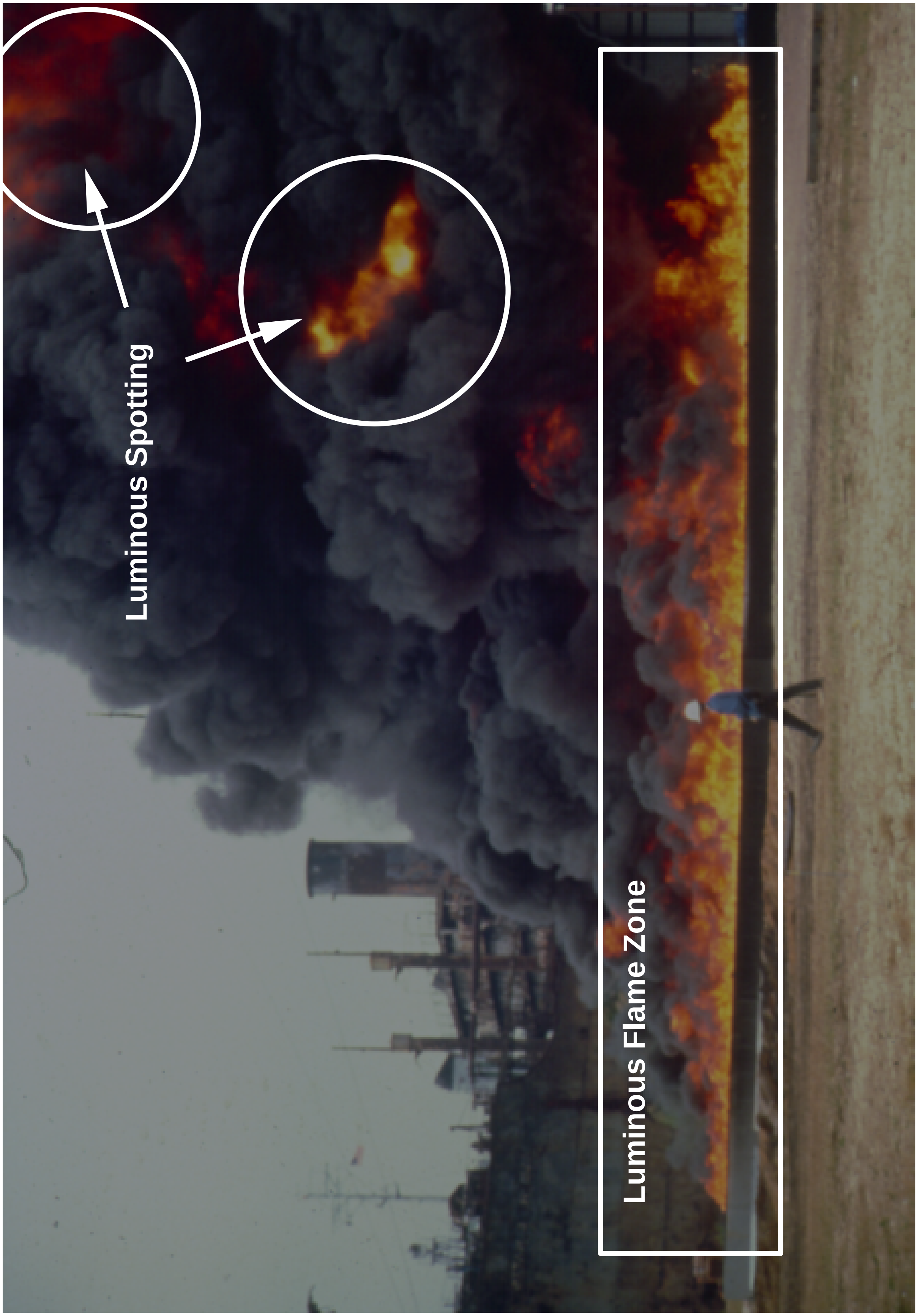

Figure 4: Photograph of a 15 m square fire of diesel fuel on water.

Mudan and Croce use an emissive power *averaged* over the flame height of the fire [4, 3]. Both correlations fall below 31.5 kW/m^2 for fires larger than 30 m in diameter (see Fig. 5). These correlations can wrongly be interpreted to mean that buildings can be built right next to sites of potentially large fires simply because the predicted flux would never exceed 31.5 kW/m^2 regardless of its distance from the fire. Because the HUD guidelines have to account for both near-field and far-field targets, and because of the importance of assessing the effectiveness of thermal barriers, the methodology for predicting radiative flux has to be applicable over the entire range of fire sizes and separation distances.

The methodology adopted here yields roughly the same product $H \cdot E_f$ as the other methods [3], however E_f will be regarded as the emissive power of the luminous flame zone (higher than the average emissive power often reported in the literature), and H will be the height of this luminous zone (lower than the flame height predicted by engineering correlations). For simplicity, a constant emissive power of 100 kW/m^2 is adopted here because it has been cited as the emissive power of the luminous spots in gasoline and kerosene fires [4]. The height of the luminous flame zone, H, can be found from Eq. 2. To simplify the analysis, the fire area is assumed circular ($P = \pi D$ and $\dot{Q} = \pi \, (D/2)^2 \, \dot{q}''_f$), but this is not a restrictive assumption. Substituting expressions for χ_r and $\dot{Q}$ into Eq. 2 yields an expression for the height H

$$H = \frac{\chi_{r_{\max}} \, e^{-kD} \, D \, \dot{q}''_f}{4 \, E_f} \tag{5}$$

H is plotted as a function of D in Fig. 8. In the plot H reaches a maximum value at $D = 20$ m (66 ft). Because of the scarcity of data about χ_r and $\dot{Q}$ for very large fires, it is assumed that for fires with diameters greater than 20 m, the height of the luminous flame zone remains at its maximum value. The maximum value of H is found by substituting D=20 m, $\chi_{r_{\max}}$=0.35, k=0.05 m^{-1}, and E_f=100 kW/m^2 into Eq. (5)

$$H_{\max} = \frac{0.35 \, e^{-1} \, 20 \, \dot{q}''_f}{4 \cdot 100} = 6.4 \times 10^{-3} \, \dot{q}''_f \tag{6}$$

where $H_{\max}$ is in units of m and $\dot{q}''_f$ in kW/m^2. Most potential fires included in hazard calculations will be greater than 20 m in diameter. In these cases, all that is required to obtain the height of the luminous zone is an estimate of the heat release rate per unit area. These values for the hazardous liquids are listed in Table 1. For fires less than 20 m in diameter, Eq. (5) can be used to obtain H.

Figure 7 compares the product of E_f and H for the three methodologies. For fires whose diameters are between 1 m and 50 m, the three methods yield similar values of $E_f \cdot H$, with the present methodology the most conservative. Beyond a 50 m fire diameter, the methods diverge, simply because the experiments upon which the correlations were based did not include any fires larger than 50 m. The HUD guidelines, however, must account for fires whose diameters are potentially hundreds of meters. The assumption made by the present methodology is that beyond roughly 20 m, the radiative energy flux per unit length of fire perimeter, $E_f \cdot H$, remains relatively constant, allowing for predictions of radiative flux from extremely large fires that have never been studied experimentally.

What remains of calculating the thermal radiation flux using Eq. 1 is determining the view factor F from the fire to a target. The view factor calculation can be simplified by assuming the fire is surrounded by a vertical wall of height H emitting radiation energy at a rate of E_f, and that

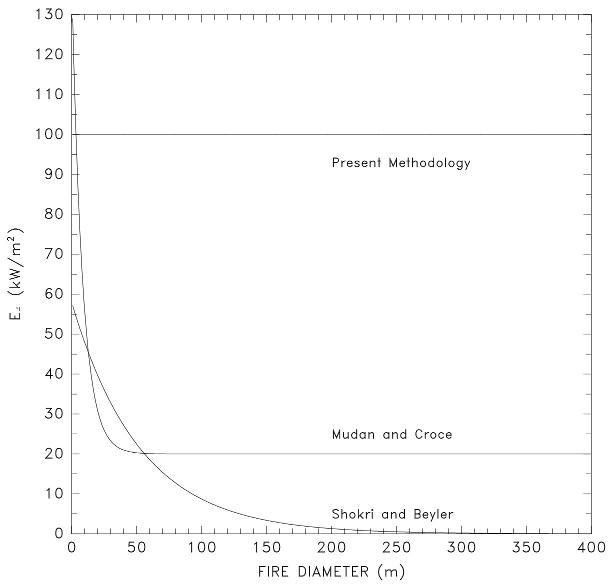

Figure 5: Emissive power as a function of fire diameter for a gasoline pool fire.

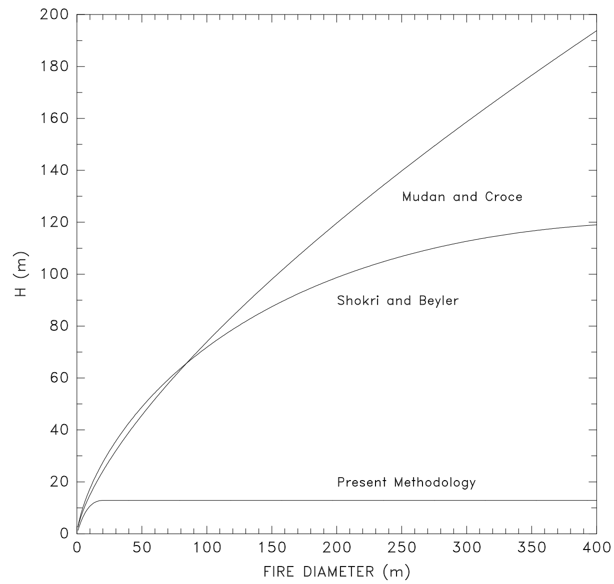

Figure 6: Flame height as a function of fire diameter for a gasoline pool fire.

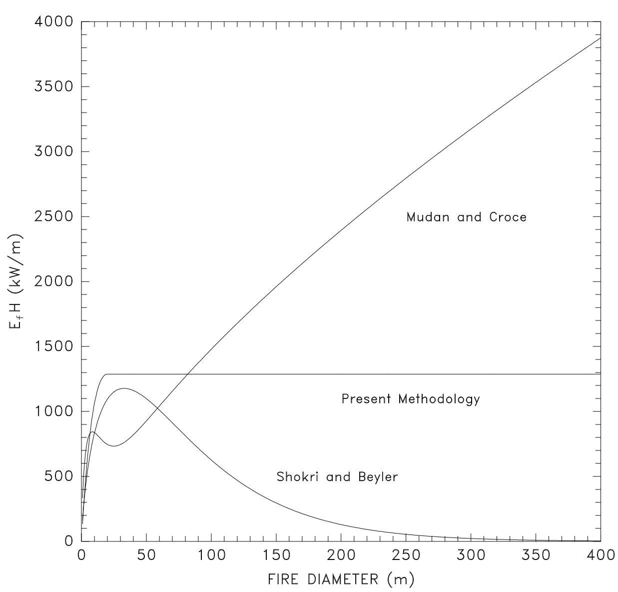

Figure 7: Radiative energy flux, $E_f \cdot H$, as a function of fire diameter for a gasoline pool fire.

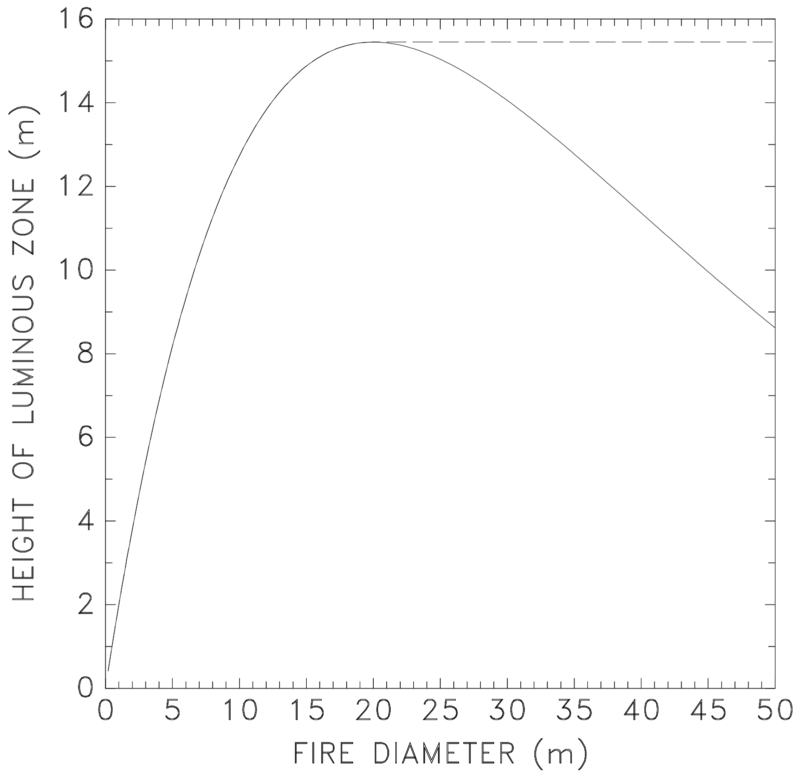

Figure 8: Height of luminous flame zone for a gasoline fire, where $\chi_{r_{\max}} = 0.35$, $\dot{q}''_f = 2400$ kW/m^2, $k = 0.05$ m^{-1}, and $E_f = 100$ kW/m^2. See Eq. (5). In general, the maximum height of the luminous flame zone of a liquid pool fire is given by $H_{\max} = 6.4 \times 10^{-3}\,\dot{q}''_f$ where $\dot{q}''_f$ is the heat release rate per unit area in units of kW/m^2. The dashed line in the figure indicates $H_{\max}$.

the wall is composed of circular or linear elements for which analytical recipes of the view factor are available.

The presence of man-made or natural thermal barriers can be incorporated into the view factor calculation. Although the methodology presented in this section is designed to be conservative, it is not conservative in one regard. Because the radiative energy output is concentrated near the base of the fire rather than distributed over the entire height of the fire, the effectiveness of a thermal barrier in blocking thermal radiation might be exaggerated. Recent measurements in Japan [8] of a 20 m diameter crude oil fire showed that 85 % of the radiant energy of the fire was emitted at heights lower than 20 m. The remaining 15 % of the radiant energy was emitted mainly by hot black smoke at higher levels, and by occasional luminous bursts of flame. The HRR per unit area, $\dot{q}''_f$, for crude oil is approximately 2,000 kW/m^2, thus according to Eq. (6), the luminous flame height for a 20 m diameter pool fire is $6.4 \times 10^{-3}\,2000 = 12.8$ m. In this context, a thermal barrier 13 m in height would be expected to block all of the thermal radiation. To remedy the situation, it is suggested that for the purpose of evaluating a thermal barrier, the emissive power of the flame be reduced by a half, from 100 kW/m^2 down to 50 kW/m^2. Energy conservation will be preserved by noting that the height of the luminous zone (Eq. (6)) will double as a result of the lower estimate of the emissive power. The quantity $E_f \cdot H$ remains the same, thus the prediction of radiative flux in the far-field remains the same. The range of emissive powers between 50 kW/m^2 and 100 kW/m^2 is not arbitrary. Many researchers have made emissive power measurements of large pool fires that fall in this range. It is a difficult measurement to make because in reality the emissive power is both spatially and temporally varying. The choices of 100 kW/m^2 for near-field hazard calculations and 50 kW/m^2 for the evaluation of thermal barriers are intended to yield conservative estimates of Acceptable Separation Distance (ASD).

3.2 Hazardous Gases

Fire scenarios involving combustible gases vary widely, from a pool fire of a liquified gas, like LNG or LPG, to a flare formed by burning vapors escaping a storage tank, to a fireball following the release of a large amount of gas that subsequently ignites. Because it is difficult to predict the structure of the fire, it is important to employ a methodology for predicting the thermal radiation flux from the fire. The simplest method of calculating the thermal radiation, known as the "point source" model, is to estimate the heat release rate of the fire, assume a fraction of the total energy is released in the form of thermal radiation, and then divide this radiated energy over the surface area of a sphere whose radius is the distance from the center of the fire to the target

$$\dot{q}'' = \frac{\chi_r \, \dot{Q}}{4\pi r^2} \tag{7}$$

Essentially, this method assumes that all of the thermal radiation emanates from a point. For targets greater than several fire diameters away, this assumption is reasonably good. However, at closer distances, the assumption is not valid, but it is conservative because it assumes all of the energy is concentrated at a point rather than spread over the height and width of the fire, as was assumed by the "solid flame" model above.

Equation 7 requires two pieces of information: the radiative fraction, χ_r, and the total HRR, $\dot{Q}$. Because gaseous fires are often in the form of flares, it is not appropriate to assume that χ_r decreases with fire diameter as in the case of liquid fires above. Flares are substantially more luminous than liquid pool fires because the oxygen is better able to penetrate the combustion region and thus the combustion is more efficient and less smoke is formed in the process. A conservative estimate of χ_r is 0.20, appropriate for a wide range of gaseous fuels [4]. The estimate of the HRR, $\dot{Q}$, is not as easy as it is for liquids because more often than not there is no fire "diameter" because there is no liquid pool – even for liquified gaseous fuels like LNG and LPG. It is more appropriate in this case to estimate a mass burning rate, $\dot{m}$, and then multiply this by a heat of combustion (see Table 2)

$$\dot{Q} = \dot{m} \, \Delta H_c \tag{8}$$

Because of the uncertainty inherent in predicting the hazard associated with pressurized storage of gases, the consideration of thermal barriers as a means of lessening the radiation flux to distant targets is difficult. Liquified gases may form a pool that erupts in fire, or the gases may vaporize so quickly that a fireball or turbulent jet fire forms. In the former case, a wall surrounding the fire may block a substantial fraction of the radiation energy, whereas in the latter case, a wall will do little to lessen the impact of thermal radiation on surrounding targets. Consequently, consideration should not be given to thermal barriers when assessing the thermal radiation hazard from fires of pressurized storage tanks or pipelines of combustible gases.

4 Determining the Acceptable Separation Distance (ASD)

This section presents a step by step method for determining the Acceptable Separation Distance (ASD) from a large fire. There are two ASD criteria – one for buildings and one for people. The ASD for buildings is the distance between the building and the fire at which the thermal radiative flux is less then 31.5 kW/m^2 (10,000 Btu/h/ft^2). For people, the flux level is 1.4 kW/m^2 (450 Btu/h/ft^2). There are two basic calculation methods available; one for hazardous liquids and one for hazardous gases. The calculation for hazardous liquids can be greatly simplified if certain criteria are met.

Hazardous Liquids:

1. Simplified Calculation: If the fuel is liquid at atmospheric temperature and pressure, if the fire is roughly circular around its base, and if there are no obstructions to be considered, go to Section 4.1 for details.

2. Detailed Calculation: If any of the criteria for the Simplified Calculation are not met, go to Section 4.2 for details.

Hazardous Gases: For hazardous gases, the thermal radiation flux is determined from Eq. 7. Due to the unpredictable nature of gaseous fire scenarios, no consideration should be given to thermal barriers. See Section 4.3 for details.

4.1 Simplified Chart for Hazardous Liquids

If the fuel is liquid at atmospheric temperature and pressure, if the fire is roughly circular around its base, and if there are no obstructions to be considered, simplified charts like Fig. 10 can be used to determine the ASD. The ASD values presented in the chart are based on the assumption that the perimeter of the fire is a circle. If this is not the case, an equivalent fire diameter needs to be calculated. If the ratio of the longest dimension to the shortest is less than 2.5, then an equivalent cylinder of diameter

$$D = \sqrt{4A/\pi} \tag{9}$$

can be assumed. Otherwise, a combination of either vertical circular arcs or vertical flat plates can be used as surrogates for the actual fire shape. A schematic diagram is shown in Fig. 9 to illustrate the point. The irregularly shaped region indicates the fire area. Rather than calculate the view factor for the actual fire, a circular cylinder of equal height can be drawn that completely obscures the view of the fire from the target. The view factor from the cylinder will be greater than that from the actual fire. If more than one target location is to be evaluated, the cylinder has to be redrawn for each location unless the cylinder is drawn so that the actual fire is completely enclosed by the boundary of the cylinder. If the actual fire region is elongated, drawing one cylinder may produce a result that is overly conservative. In cases such as these, the analysis can include more than one cylinder or a direct calculation of the thermal radiation flux can be performed based on adding the view factors of a collection of vertical plates and cylinders (see next section).

Once the equivalent fire diameter has been determined, the ASD for people and/or buildings can be obtained from Fig. 10. This chart displays the distance from a fire at which the radiative flux is expected to be 31.5 kW/m^2 (10,000 Btu/h/ft^2) and 1.4 kW/m^2 (450 Btu/h/ft^2), respectively. Note that the ASD is measured from the leading edge of the fire. A useful feature of the chart is that it shows that there are maximum separation distances from a fire beyond which the thermal radiation flux impinging on a structure or person is less than the ASD threshold values regardless of the fire size. Table 1 lists these maximum values for the different fuels considered. The values are obtained by extrapolating the ASD from Fig. 10 for extremely large fire diameters. These maximum ASD values can be used as "screening" values because distances greater than the "Screen ASD" meet the criteria for thermal radiation flux regardless of fire size. Another useful application of "Screen ASD" is in cases where the fuel spill is unconfined. The 1975 HUD guidelines [2] and the SFPE Handbook [4] discuss methods of estimating the diameter of an unconfined spill fire. The simplest method of obtaining a spill diameter is

$$D = 10\sqrt{V} \tag{10}$$

where D is in meters and V is in cubic meters [1]. Equation 10 asserts that the liquid will continue to spread until it is about 1 cm in depth. However, given the wide variety of potential spill scenarios and the number of assumptions that have to be made in order to apply the correlations, it is preferable to apply the "Screen ASD" distances in cases of unconfined spills rather than relying on the spill diameter correlations.

4.2 Detailed Calculation for Hazardous Liquids

In cases involving liquid fuel fires for which the simplified chart, Fig. 10, discussed in Section 4.1 is not appropriate, a more detailed calculation is required. Specifically, if physical obstructions like thermal barriers are being considered or if the fire is not circular or does not easily yield an equivalent diameter suitable for the simplified method, then the thermal radiation flux must be calculated directly. The thermal radiation flux at a particular location is given by the expression

$$\dot{q}'' = F\, E_f \tag{11}$$

The emissive power E_f for liquids is assumed to be 100 kW/m^2. The view factor F can be calculated by assuming the fire perimeter to be made up of circular arcs or straight lines. If the fire perimeter is irregularly shaped, cylinders or vertical plates can be used as surrogates for the perimeter as long as they completely block the view of the fire from the observer. The view factor for a cylinder of height H and diameter D at a target that is a distance S away from the nearest point on the cylinder (see Fig. 12) can be obtained from Table 3. The view factor for a vertical plate of height H and width W at a target a distance S from the center of the plate and distance S' from the centerline can be obtained from the formula

$$F(S,S',H,W) = \begin{cases} \dfrac{F(S,0,H,2S'+W) - F(S,0,H,2S'-W)}{2} & 2S' > W \\[2ex] \dfrac{F(S,0,H,2S'+W) + F(S,0,H,W-2S')}{2} & 2S' < W \end{cases} \tag{12}$$

Note that Table 4 yields view factors only when the target is equally distant from the two ends of the plate, *i.e.* when $S' = 0$. Thus, $F(S,0,H,W)$ indicates the view factor obtained directly from

[1] The equivalent formula in English units is $D = 2\sqrt{V}$ where D is in feet and V is in gallons.

Table 4. In order to obtain the view factor for targets not equally distant from the two ends of the plate ($S' \neq 0$), the above formula must be used.

Some methods of calculating radiation flux from large fires take into account the "tilting" of the fire due to the wind [4]. Essentially, a more complicated calculation of the view factor from a tilted plate or cylinder is performed. The results are only marginally different than those obtained for vertical plates and cylinders when the target is beyond a few fire diameters away. The difference in results is well within the factor of safety inherent in the calculation procedure resulting from the conservative estimates of the principal parameters.

A common way to mitigate the thermal flux from a large fire is to build a barrier between the site of a potential fire and the site to be protected. Assuming the barrier remains intact during the fire, it will serve to reduce the view factor whose calculation was described above. In the simplest case, it can be assumed that a barrier of height x will reduce the thermal flux to a target by a factor of x/H if the target is at ground level and the barrier is long enough to block the view of the fire at each end. If the barrier only partially obscures the width of the fire, then the view factor can be obtained by adding the view factors of the exposed sections of the luminous wall of flames. In other words, only those sections of the luminous wall of flames visible to the potential target need to be considered in the radiation flux calculation. If these sections of the luminous wall of flame are not connected, the radiation flux at the target can be obtained by adding the view factors of each of the exposed sections together.

4.3 Point Source Model for Combustible Gases

For combustible gases stored under pressure, whether in liquid or vapor form, it is difficult to predict exactly how the gas will burn in the event of a fire. In liquified form, like LNG or LPG, the liquid will either spill out of the container and form a pool, or it will vaporize so rapidly that it will never form a pool. It depends on the size of the tank rupture and the amount of liquid available. To make a prediction of the thermal radiation flux, one needs to know, at a minimum, the mass burning rate of the liquid/gas. The mass burning rate of the liquid/gas can be assumed to be the rate at which the liquid/gas is escaping the tank. The total HRR of the fire is estimated by multiplying the mass burning rate by the heat of combustion (see Table 2). Then, Eq. (7) is applied to predict the thermal radiation flux at a target.

Liquid	Mass Burning Rate, $\dot{m}''$	Heat of Combustion	HRR Per Unit Area, $\dot{q}''_f$	Screen ASD		Reference
				Struct.	People	
	kg/m^2/s	kJ/kg	kW/m^2	m	m	
Acetic Acid	0.033	13,100	400	10	90	Ref. [10]
Acetone	0.041	25,800	1,100	10	250	Ref. [9]
Acrylonitrile	0.052	31,900	1,700	15	390	Ref. [10]
Amyl Acetate	0.102	32,400	3,300	30	750	Ref. [10]
Amyl Alcohol	0.069	34,500	2,400	20	550	Ref. [10]
Benzene	0.048	44,700	2,100	20	480	Ref. [9]
Butyl Acetate	0.100	37,700	3,800	35	860	Ref. [10]
Butyl Alcohol	0.054	35,900	1,900	15	430	Ref. [10]
m-Cresol	0.082	32,600	2,700	25	620	Ref. [10]
Crude Oil	0.045	42,600	1,900	15	430	Ref. [9]
Cumene	0.132	41,200	5,400	50	1220	Ref. [10]
Cyclohexane	0.122	43,500	5,300	45	1200	Ref. [10]
No. 2 Diesel Fuel	0.035	39,700	1,400	12	320	Ref. [9]
Ethyl Acetate	0.064	23,400	1,500	15	340	Ref. [10]
Ethyl Acrylate	0.089	25,700	2,300	20	530	Ref. [10]
Ethyl Alcohol	0.015	26,800	400	10	90	Ref. [9]
Ethyl Benzene	0.121	40,900	4,900	40	1100	Ref. [10]
Ethyl Ether	0.094	33,800	3,200	30	730	Ref. [10]
Gasoline	0.055	43,700	2,400	20	550	Ref. [9]
Hexane	0.074	44,700	3,300	30	750	Ref. [9]
Heptane	0.101	44,600	4,500	40	1000	Ref. [9]
Isobutyl Alcohol	0.054	35,900	1,900	15	430	Ref. [10]
Isopropyl Acetate	0.073	27,200	2,000	20	460	Ref. [10]
Isopropyl Alcohol	0.046	30,500	1,400	15	320	Ref. [10]
JP-4	0.051	43,500	2,200	20	500	Ref. [9]
JP-5	0.054	43,000	2,300	20	530	Ref. [9]
Kerosene	0.039	43,200	1,700	15	400	Ref. [9]
Methyl Alcohol	0.017	20,000	340	10	80	Ref. [9]
Methyl Ethyl Ketone	0.072	31,500	2,300	20	530	Ref. [10]
Pentane	0.126	45,000	5,700	50	1300	Ref. [10]
Toluene	0.112	40,500	4,500	40	1000	Ref. [10]
Vinyl Acetate	0.136	22,700	3,100	25	700	Ref. [10]
Xylene	0.090	40,800	3,700	30	850	Ref. [9]

Table 1: Burning rate data for hazardous liquids taken from Refs. [9, 10]. For many liquids on the list, mass burning rate data are unavailable, in which case a correlation has been used, $\dot{m}'' = 0.001\ \Delta H_c/\Delta H_v$ kg/m^2/s, where ΔH_c is the heat of combustion and ΔH_v is the heat of vaporization [4]. The heats of combustion and vaporization can be found in Appendix A of Ref. [10]. The "HRR Per Unit Area" refers to the total energy generated by the fire per unit area of the liquid pool. It is obtained by multiplying the "Mass Burning Rate" by the "Heat of Combustion". The "Screen ASD" is the distance beyond which the thermal radiation flux criteria is satisfied, regardless of fire size.

Gas	Mass Burning Rate	Heat of Combustion	Heat Release Rate Per Unit Area, $\dot{q}_f''$	Reference
	$kg/m^2/s$	kJ/kg	kW/m^2	
Liquified Gases (Cryogenics)				
Liquid H_2	0.02	120,000	2,400	Ref. [9]
LNG	0.08	50,000	4,000	Ref. [9]
LPG	0.10	46,000	4,600	Ref. [9]
Gases				
Acetaldehyde	N/A	25,100	N/A	Ref. [10]
Butadene	N/A	45,500	N/A	Ref. [10]
Butane	N/A	45,400	N/A	Ref. [10]
Ethane	N/A	47,200	N/A	Ref. [10]
Ethylene	N/A	47,200	N/A	Ref. [10]
Ethylene Oxide	N/A	27,700	N/A	Ref. [10]
Methane	N/A	50,000	N/A	Ref. [10]
Propane	N/A	46,000	N/A	Ref. [10]
Propylene	N/A	45,800	N/A	Ref. [10]
Vinyl Chloride	N/A	16,900	N/A	Ref. [10]

Table 2: Burning rate data for hazardous gases taken from Refs. [9, 10]. The "Heat Release Rate Per Unit Area" refers to the total energy generated by the fire per unit area of the base. Note that this is only appropriate for the cryogenics because they can potentially form a pool.

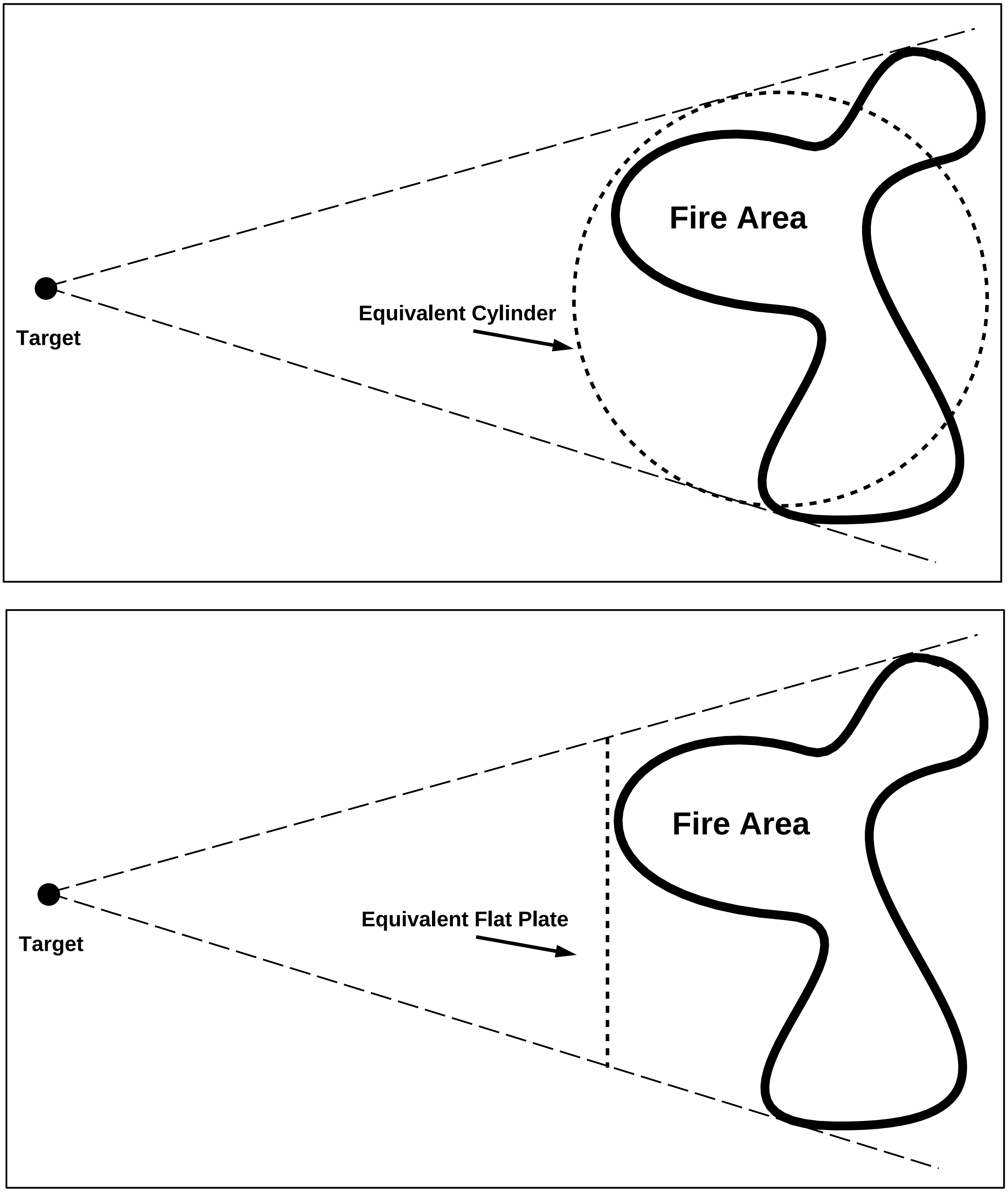

Figure 9: Schematic diagram showing how a cylinder or flat vertical plate can be used to simplify a view factor calculation.

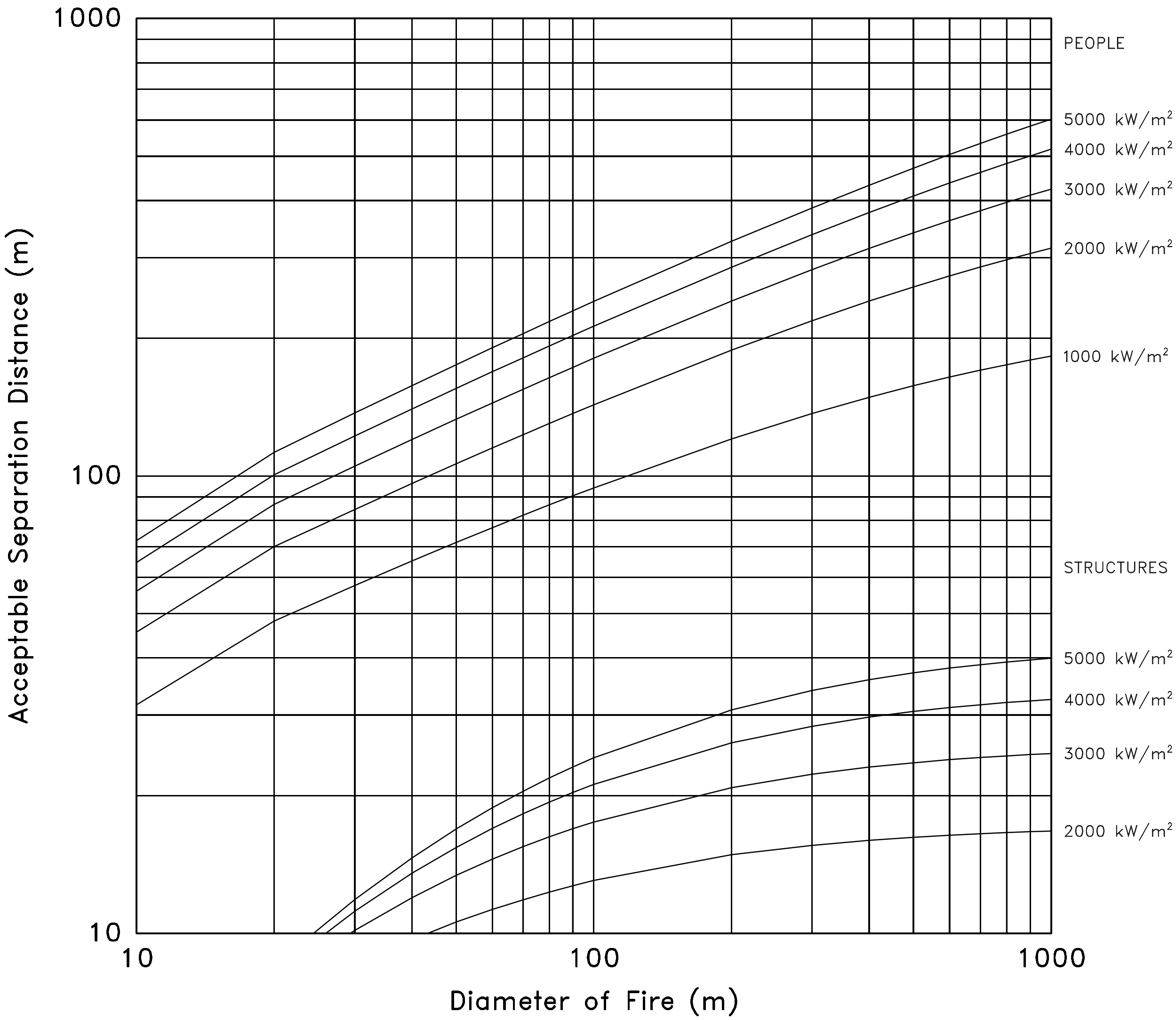

Figure 10: Acceptable Separation Distance (ASD) from nearly cylindrical fires resulting from spills of hazardous liquids, metric units. The upper curves are ASDs for people, the lower curves for combustible structures. The numbers associated with each curve are heat release rates per unit area of burning surface, $\dot{q}_f''$, in units of kW/m^2. These values for various fuels are obtained from Table 1.

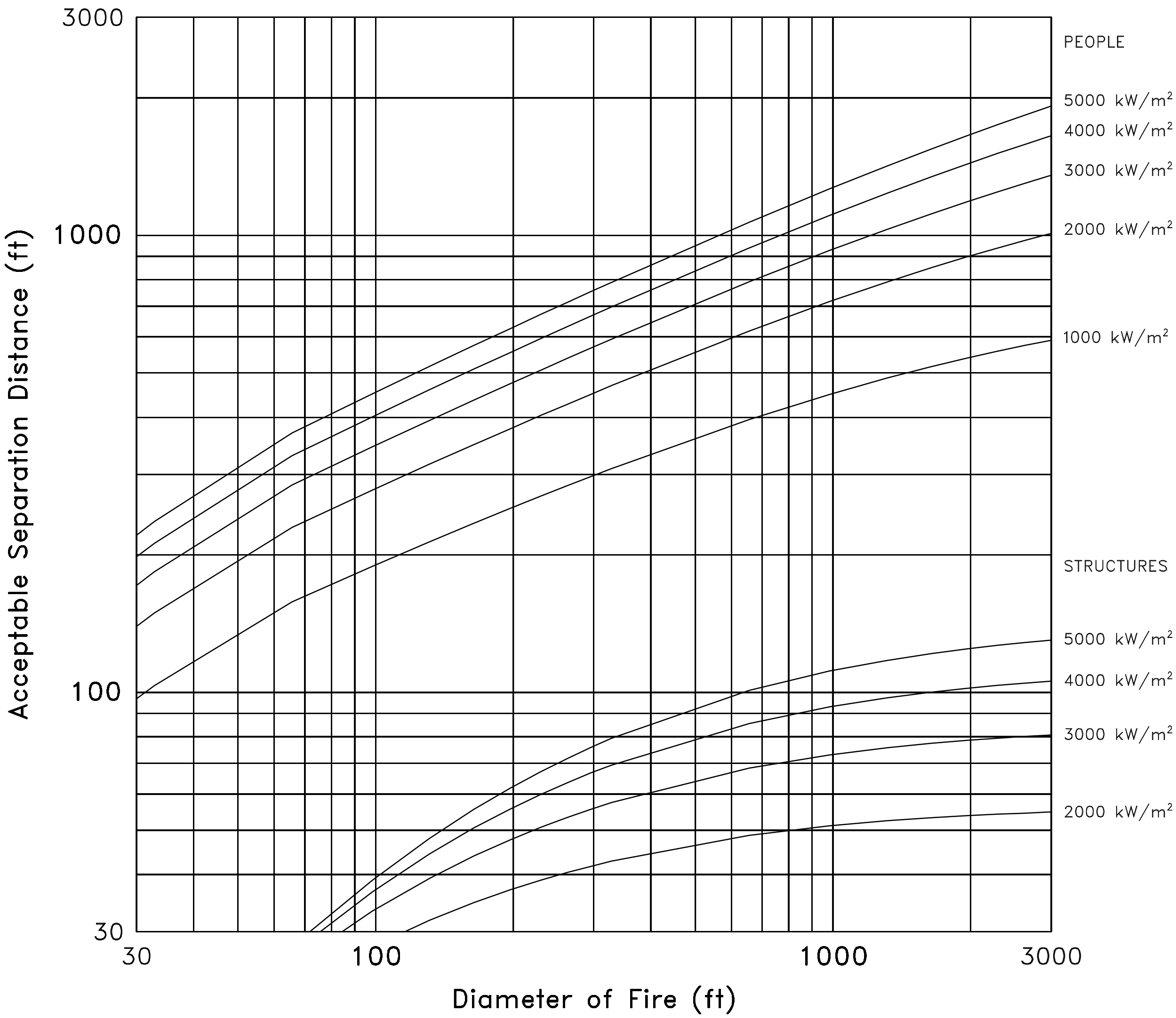

Figure 11: Acceptable Separation Distance (ASD) from nearly cylindrical fires resulting from spills of hazardous liquids, English units. The upper curves are ASDs for people, the lower curves for combustible structures. The numbers associated with each curve are heat release rates per unit area of burning surface, $\dot{q}''_f$, in units of kW/m^2. These values for various fuels are obtained from Table 1.

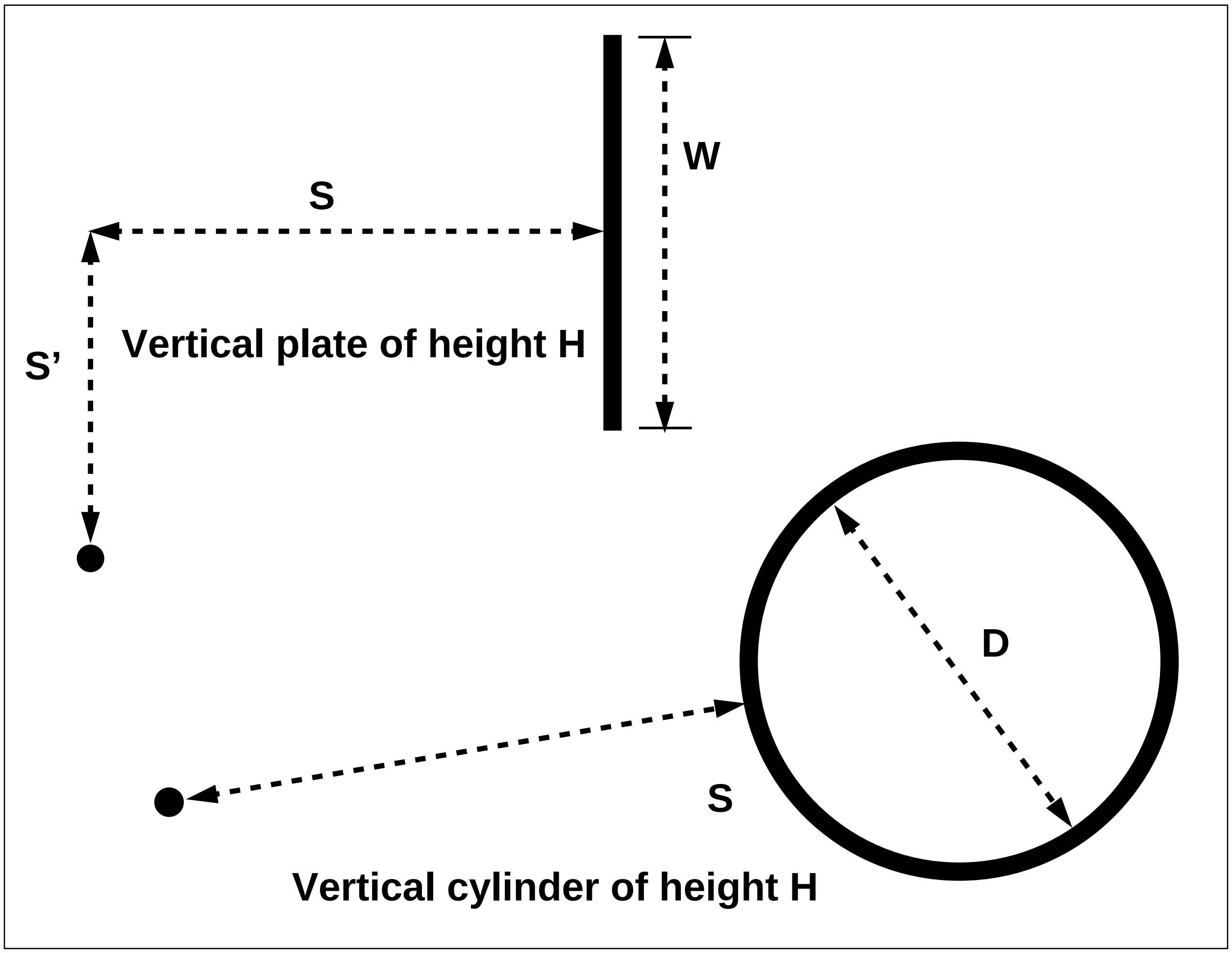

Figure 12: Notation used in view factor calculations.

S/D	H/D																		
	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.1	0.044	0.087	0.128	0.166	0.201	0.233	0.262	0.288	0.311	0.331	0.442	0.481	0.497	0.506	0.510	0.513	0.515	0.517	0.518
0.2	0.019	0.039	0.058	0.077	0.095	0.113	0.130	0.146	0.162	0.177	0.289	0.349	0.380	0.399	0.410	0.417	0.422	0.425	0.427
0.3	0.012	0.023	0.035	0.046	0.057	0.068	0.079	0.090	0.101	0.111	0.198	0.256	0.294	0.318	0.334	0.344	0.352	0.357	0.361
0.4	0.008	0.016	0.024	0.031	0.039	0.047	0.054	0.062	0.069	0.076	0.142	0.193	0.230	0.256	0.274	0.287	0.297	0.304	0.310
0.5	0.006	0.011	0.017	0.023	0.029	0.034	0.040	0.045	0.051	0.056	0.107	0.149	0.183	0.208	0.227	0.242	0.253	0.261	0.268
0.6	0.004	0.009	0.013	0.017	0.022	0.026	0.030	0.035	0.039	0.043	0.084	0.119	0.148	0.172	0.190	0.205	0.217	0.226	0.233
0.7	0.003	0.007	0.010	0.014	0.017	0.021	0.024	0.028	0.031	0.034	0.067	0.096	0.122	0.143	0.161	0.175	0.187	0.196	0.204
0.8	0.003	0.006	0.008	0.011	0.014	0.017	0.020	0.022	0.025	0.028	0.055	0.080	0.102	0.121	0.137	0.151	0.162	0.172	0.180
0.9	0.002	0.005	0.007	0.009	0.012	0.014	0.016	0.019	0.021	0.023	0.046	0.067	0.086	0.103	0.118	0.131	0.142	0.151	0.159
1.0	0.002	0.004	0.006	0.008	0.010	0.012	0.014	0.016	0.018	0.020	0.039	0.057	0.074	0.089	0.102	0.114	0.125	0.134	0.141
2.0	0.001	0.001	0.002	0.002	0.003	0.004	0.004	0.005	0.005	0.006	0.012	0.018	0.024	0.030	0.035	0.040	0.045	0.050	0.055
3.0	0.000	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003	0.006	0.009	0.012	0.015	0.017	0.020	0.023	0.025	0.028
4.0	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.003	0.005	0.007	0.009	0.010	0.012	0.014	0.015	0.017
5.0	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.005	0.006	0.007	0.008	0.009	0.010	0.011
6.0	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.002	0.002	0.003	0.004	0.005	0.006	0.006	0.007	0.008
7.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002	0.002	0.003	0.004	0.004	0.005	0.005	0.006
8.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.002	0.003	0.003	0.004	0.004	0.005
9.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002	0.002	0.003	0.003	0.003	0.004
10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003

Table 3: View Factors from a Cylinder to an Element Receiving Maximum Radiation [4]. Note that H is the height of the cylinder, D is the diameter of the cylinder, and S is the distance from the leading edge of the fire to the element. The element is assumed to be at the same elevation as the base of the cylinder. See Fig. 12 for a schematic diagram.

S/W	H/W																		
	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.1	0.050	0.098	0.143	0.185	0.223	0.256	0.286	0.311	0.333	0.352	0.444	0.470	0.480	0.484	0.486	0.488	0.489	0.489	0.489
0.2	0.024	0.049	0.072	0.096	0.118	0.140	0.161	0.181	0.200	0.218	0.343	0.401	0.428	0.442	0.450	0.455	0.457	0.459	0.461
0.3	0.016	0.031	0.047	0.062	0.077	0.092	0.106	0.120	0.134	0.148	0.257	0.325	0.364	0.387	0.401	0.409	0.415	0.418	0.421
0.4	0.011	0.022	0.033	0.044	0.055	0.065	0.076	0.086	0.096	0.107	0.195	0.259	0.302	0.330	0.348	0.360	0.368	0.373	0.377
0.5	0.008	0.016	0.024	0.033	0.041	0.049	0.057	0.065	0.072	0.080	0.151	0.206	0.248	0.277	0.298	0.312	0.322	0.329	0.335
0.6	0.006	0.013	0.019	0.025	0.031	0.038	0.044	0.050	0.056	0.062	0.118	0.166	0.203	0.232	0.253	0.269	0.281	0.289	0.296
0.7	0.005	0.010	0.015	0.020	0.025	0.030	0.035	0.039	0.044	0.049	0.095	0.135	0.168	0.195	0.216	0.232	0.244	0.253	0.261
0.8	0.004	0.008	0.012	0.016	0.020	0.024	0.028	0.032	0.036	0.040	0.077	0.111	0.140	0.164	0.184	0.200	0.212	0.222	0.230
0.9	0.003	0.007	0.010	0.013	0.016	0.020	0.023	0.026	0.029	0.033	0.064	0.093	0.118	0.140	0.158	0.173	0.185	0.195	0.203
1.0	0.003	0.005	0.008	0.011	0.014	0.016	0.019	0.022	0.025	0.027	0.054	0.078	0.100	0.120	0.136	0.151	0.162	0.172	0.180
2.0	0.001	0.002	0.002	0.003	0.004	0.005	0.005	0.006	0.007	0.008	0.015	0.023	0.030	0.037	0.043	0.050	0.056	0.061	0.066
3.0	0.000	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003	0.003	0.007	0.010	0.014	0.017	0.020	0.023	0.027	0.030	0.032
4.0	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.004	0.006	0.008	0.010	0.012	0.014	0.015	0.017	0.019
5.0	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.004	0.005	0.006	0.008	0.009	0.010	0.011	0.012
6.0	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.004	0.004	0.005	0.006	0.007	0.008	0.009
7.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.002	0.003	0.003	0.004	0.005	0.005	0.006	0.006
8.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.002	0.003	0.003	0.004	0.004	0.005
9.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.002	0.002	0.003	0.003	0.004	0.004
10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003	0.003

Table 4: View Factors from a Flat Vertical Plate to an Element Receiving Maximum Radiation [11]. Note that H is the height of the plate, W is the width of the plate, and S is the distance from the center of the base of the plate to the element. The element is assumed to be at the same elevation as the base of the plate. See Fig. 12 for a schematic diagram.

5 Sample Problems

The following example problems present a step by step method for applying the procedure outlined above.

5.1 Problem 1

A gasoline storage tank is located in a circular dike 12 m (40 ft) in diameter. What is the Acceptable Separation Distance (ASD) from this site. In other words, in the event of a tank rupture and fire, would buildings or other combustible structures in the vicinity be exposed to a thermal radiation flux in excess of 31.5 kW/m^2 (10,000 Btu/h/ft^2)? Would people in exposed areas be exposed to a thermal radiation flux in excess of 1.4 kW/m^2 (450 Btu/h/ft^2)?

Solution: The shape of the dike is circular and no thermal barriers are to be evaluated, thus the precomputed charts may be used to determine the ASD in this case. The HRR Per Unit Area, $\dot{q}_f''$, for gasoline is given in Table 1 as 2,400 kW/m^2. From Fig. 13, it can be seen that a fire diameter of 12 m yields an ASD of less than 10 m (33 ft) for buildings and 55 m (180 ft) for people. These distances should be applied from the edge of the dike closest to the potential target, not from the center of the dike.

Comment: The diameter of the fire is less than 20 m. According to the analysis of Section 3.1, the height of the luminous flame zone would be less than the maximum. For the simple problem above, there is no need to compute the height of the luminous zone because that is incorporated into the chart shown in Fig. 13. However, if the dike were of some irregular shape or thermal barriers were to be evaluated, the height of the luminous flame zone would need to be computed. To estimate the height, refer to Eq. (5)

$$H = \frac{\chi_{r_{\max}}\, e^{-kD}\, D\, \dot{q}_f''}{4\, E_f} = \frac{0.35 \times e^{-0.05\times 12} \times 12 \times 2,400}{4 \times 100} = 13.8 \quad \text{m}$$

The HRR Per Unit Area, $\dot{q}_f''$, for gasoline is given in Table 1 as 2,400 kW/m^2. The emissive power of the flame, E_f, is assumed to be 100 kW/m^2.

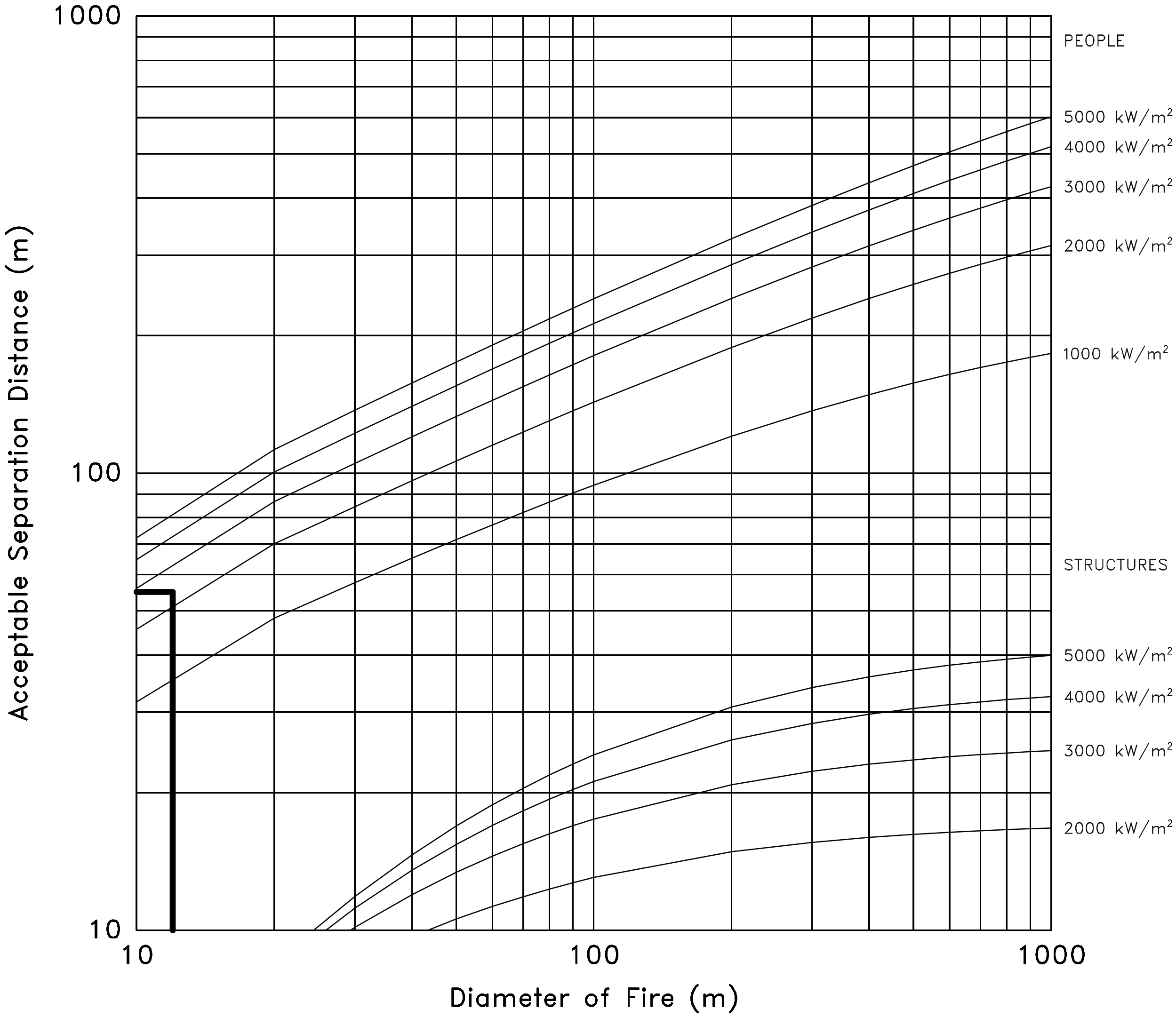

Figure 13: Solution procedure for Problem 1.

5.2 Problem 2

A gasoline storage tank is located in a diked area of 30 m by 15 m or 450 m^2 (100 ft by 50 ft or 5,000 ft^2). What is the Acceptable Separation Distance (ASD) from this site. In other words, in the event of a tank rupture and fire, would buildings or other combustible structures in the vicinity be exposed to a thermal radiation flux in excess of 31.5 kW/m^2 (10,000 Btu/h/ft^2)? Would people in exposed areas be exposed to a thermal radiation flux in excess of 1.4 kW/m^2 (450 Btu/h/ft^2)?

Solution: The shape of the dike is not circular, but its aspect ratio is less than 2.5, thus it can be assumed that the fire is cylindrical. The area of the spill region is $A = 450$ m^2. The equivalent diameter is obtained from Eq. (9)

$$D = \sqrt{4A/\pi} = 24 \text{ m} \quad (80 \text{ ft})$$

The HRR Per Unit Area for gasoline is given in Table 1 as 2,400 kW/m^2. From Fig. 14, it can be seen that a fire diameter of 24 m yields an ASD of less than 10 m (33 ft) for buildings and 85 m (295 ft) for people. These distances should be applied from the edge of the dike closest to the potential target, not from the center of the dike.

5.3 Problem 3

An undiked 114 m^3 (30,000 gal) pressurized LPG tank is located 260 m (850 ft) from a site for a proposed housing project. In the event of a tank rupture and fire, would buildings or other combustible structures in the housing complex be exposed to a thermal radiation flux in excess of 31.5 kW/m^2 (10,000 Btu/h/ft^2)? Would people in exposed areas be exposed to a thermal radiation flux in excess of 1.4 kW/m^2 (450 Btu/h/ft^2)?

Solution: Assuming the spill happens quickly, compute the diameter of the liquid pool from Eq. (10), $D = 10\sqrt{V} = 10\sqrt{114} = 107$ m. The area of the fire base is $A = \pi(D/2)^2 = \pi(107/2)^2 = 8,992$ m^2. The HRR of the fire is estimated by multiplying the area by the heat release rate per unit area from Table 2: $\dot{Q} = A\,\dot{q}''_f = 8,992 \times 4,600 = 41.4 \times 10^6$ kW. Using the point source radiation model for hazardous gases, Eq. (7), the thermal radiation flux to a target 260 m away is

$$\dot{q}'' = \frac{\chi_r\,\dot{Q}}{4\pi\,r^2} = \frac{0.20 \times 41.4 \times 10^6}{4\pi \times 260^2} = 9.7 \quad \text{kW/m}^2 \quad (3{,}100 \text{ Btu/h/ft}^2)$$

Findings: A thermal radiation flux of 9.7 kW/m^2 meets the ASD criteria for buildings, but not people. In light of the volatile nature of LPG, no consideration of thermal barriers should be given. To calculate the ASD for this scenario, rewrite Eq. (7) in terms of r

$$r = \sqrt{\frac{\chi_r\,\dot{Q}}{4\pi\,\dot{q}''}} = \sqrt{\frac{0.20 \times 41.4 \times 10^6}{4\pi \times 1.4}} = 690 \quad \text{m (2,200 ft)}$$

where $\dot{q}'' = 1.4$ kW/m^2 is the ASD criteria for people.

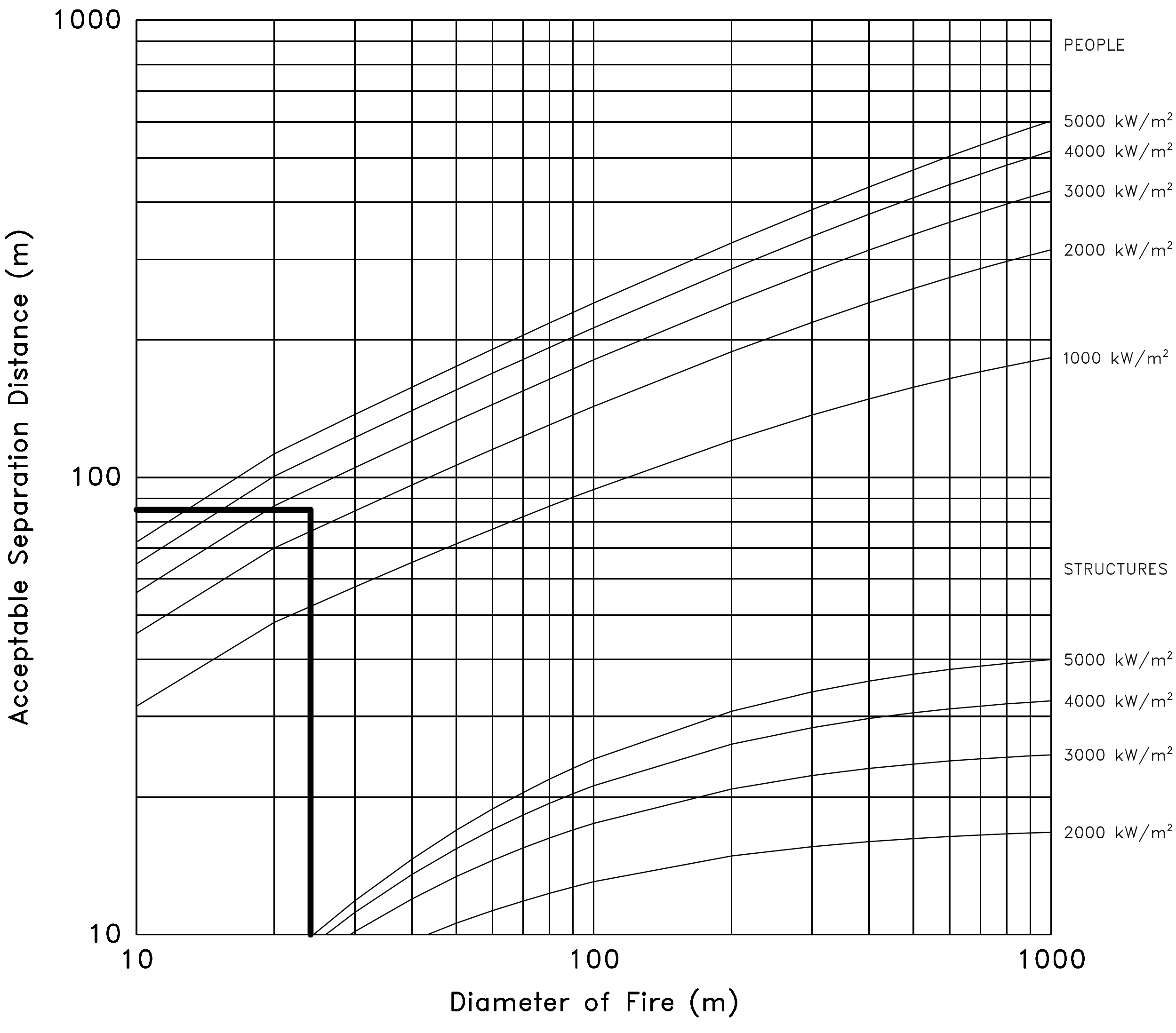

Figure 14: Solution procedure for Problem 2.

5.4 Problem 4

Fig. 15 is a plan view of a gasoline tank farm separated from a shopping complex by a road. The tank farm consists of three diked areas where a fire could erupt following the rupture of one of the tanks. Assume for this example that gasoline from one of the tanks in the middle trench spills and catches fire. Would buildings or other combustible structures in the shopping area be exposed to a thermal radiation flux in excess of 31.5 kW/m^2 (10,000 Btu/h/ft^2)? Would people in the parking area be exposed to a thermal radiation flux in excess of 1.4 kW/m^2 (450 Btu/h/ft^2)?

Step 1: Screening Distances. Table 1 lists ASD values for gasoline fires regardless of fire size. These should be considered first before any further analysis. For buildings Table 1 lists 20 m as the ASD from the leading edge of a gasoline fire, regardless of size. The buildings across the road from the fire in Fig. 15 are at least 85 m away from the fire, and thus satisfy the ASD requirement for buildings. The screening distance listed in Table 1 for people, 550 m, is greater than 55 m, the distance from the fire to the parking lot, thus a more detailed analysis of the situation must be performed. Proceed to Step 2.

Step 2: Consider the Chart. The shape of the central dike is not circular, and the aspect ratio of its longest dimension to its shortest is greater than 2.5, thus it is not appropriate to assume that the fire is cylindrical with diameter $\sqrt{4A/\pi}$. Further, thermal barriers have been proposed as a mitigator of thermal radiation, thus a direct calculation of the radiation flux to a target in the parking area needs to be made. The simplified chart in Fig. 10 is not appropriate here.

Step 3: Detailed Calculation. The fuel being spilled is gasoline. From Table 1, the heat release rate per unit area for gasoline is $\dot{q}_f'' = 2,400$ kW/m^2. Applying Eq. 6, the height of the luminous zone for a fire greater than 20 m in diameter is

$$H = 6.4 \times 10^{-3}\, \dot{q}_f'' = 15.4 \text{ m} \quad \text{(50 ft)}$$

Because the diked area is rectangular in shape, the fire perimeter can be approximated as four vertical plates, 15.4 m high. The view factor from the plate nearest the roadway is 0.079 based on Table 4 ($H = 15.4$ m, $W = 60$ m, $S = 55$ m, $S' = 0$ m, $H/W = 0.26$ and $S/W = 0.9$). The emissive power of the flame is 100 kW/m^2 based on the discussion in Section 3.1 and Fig. 5. A person in the parking lot directly across the roadway from the fire would be exposed to a thermal radiation flux of

$$\dot{q}'' = F \times E_f = 0.079 \times 100 = 7.9 \quad \text{kW/m}^2 \quad \text{(2,500 Btu/h/ft}^2\text{)}$$

This flux level exceeds the ASD standard. To determine how far one must be from the fire in order to satisfy the standard, the view factor must be less than 0.014. Referring again to Table 4, for a ratio $H/W = 0.26$, the ratio S/W must be at least 2.5 for the view factor to fall below 0.014. Since $W = 60$ m, S must be at least 2.5 times 60 m or 150 m.

Step 4: Evaluation of Thermal Barrier. It is proposed that a 7.3 m (24 ft) wall be constructed at the boundary of the tank farm to shield the shopping complex from thermal radiation. Will the wall reduce the ASD such that the parking area across the road is no longer in excess of the thermal radiation requirement for people? For this calculation, the height of the luminous flame zone is

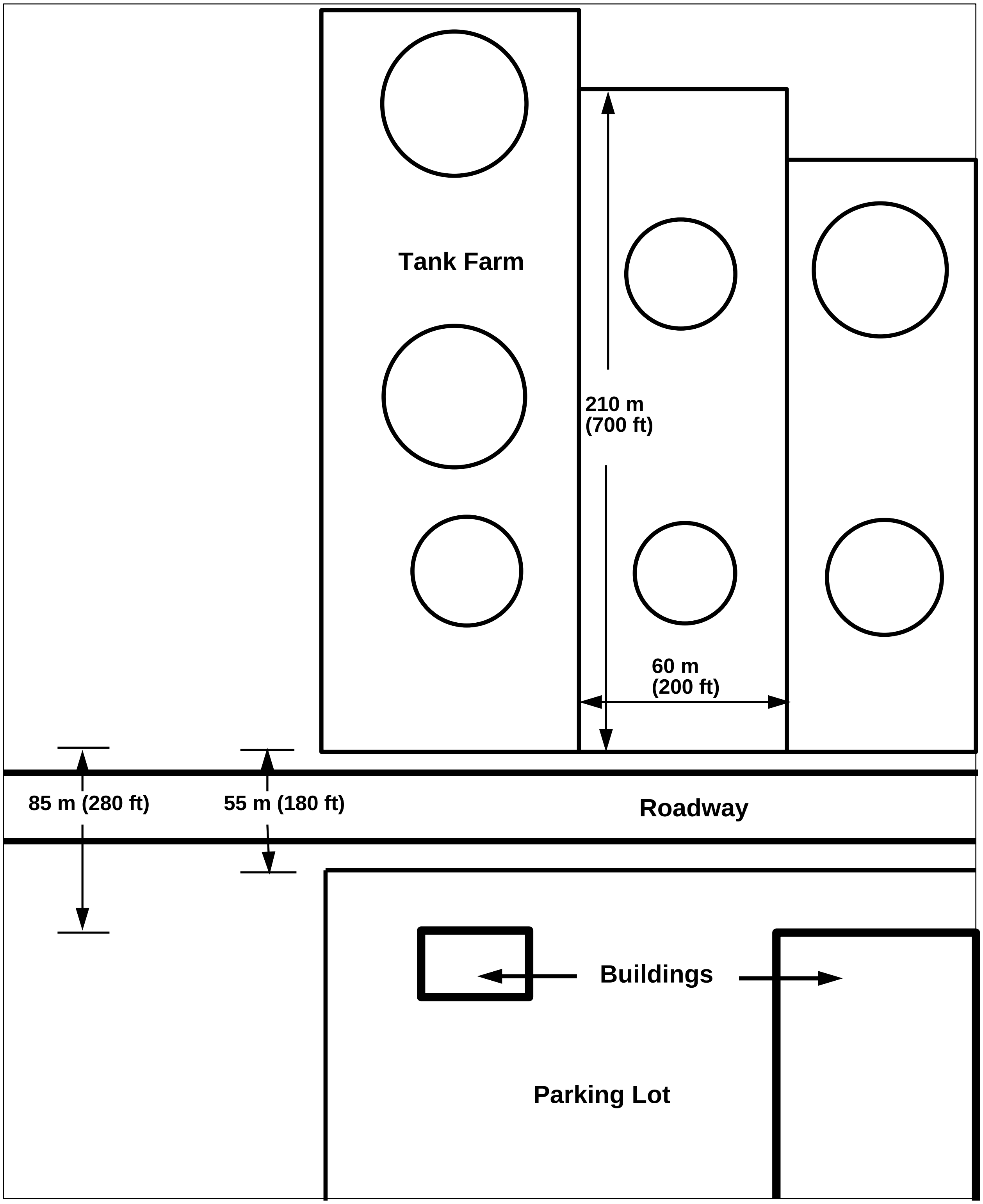

Figure 15: Plan view of gasoline tank farm and shopping complex. Note the diagram is not drawn to scale.

doubled[2] to 30.8 m and the emissive power reduced to 50 kW/m^2. The thermal barrier reduces the height of the luminous band as seen by targets farther away from 30.8 m to $30.8 - 7.3 = 23.5$ m. Now, the view factor from the plate nearest the roadway is 0.118 based on Table 4 ($H = 23.5$ m, $W = 60$ m, $S = 55$ m, $S' = 0$ m, $H/W = 0.39$ and $S/W = 0.92$). A person in the parking lot directly across the roadway from the fire would be exposed to a thermal radiation flux of

$$\dot{q}'' = F \times E_f = 0.118 \times 50 = 5.9 \quad \text{kW/m}^2 \quad (1{,}870 \text{ Btu/h/ft}^2)$$

This is still in excess of the ASD guidelines, 1.4 kW/m^2 (450 Btu/h/ft^2). To determine how far one must be from the fire in order to satisfy the standard, the view factor must be less than 0.028. Referring again to Table 4, for a ratio $H/W = 0.39$, the ratio S/W must be at least 2.0 for the view factor to fall below 0.028. Since $W = 60$ m, S must be at least 2.0 times 60 m or 120 m.

Findings: The siting of the shopping complex satisfies the ASD for buildings, but not the ASD for people. The construction of a 7.3 m (24 ft) wall would still not satisfy the ASD for people.

Comment: This example points out a few differences between the methodology developed above and the recommended standard practices outlined in the SFPE Engineering Guide [3]. For example, if one were to apply the detailed method of Shokri and Beyler, the emissive power of the fire would be given by the expression

$$E_f = 58 \times 10^{-0.00823D} = 16.1 \quad \text{kW/m}^2$$

where D is assumed to be the equivalent diameter of the 60 m by 60 m square nearest the road (67.7 m). The flame height would be given by

$$H = 0.23\,\dot{Q}^{2/5} - 1.02\,D = 67.8 \text{ m}$$

The view factor for a cylinder of height 67.8 m and diameter 67.7 m to a target 55 m away from the leading edge of the cylinder is 0.180, thus the radiation heat flux to the nearest target in the parking lot would be 2.9 kW/m^2. This figure is lower than that obtained in Step 3 above (7.9 kW/m^2) for three reasons: (1) In the Shokri and Beyler method, the radiation heat flux is assumed to be distributed over a cylinder roughly 4 times taller than the vertical plate assumed in Step 3 above. This increases the distance between the energy source and the target. (2) The equivalent cylinder in the Shokri and Beyler method is effectively farther from the target than the vertical plate assumed in Step 3 because it curves away from the front wall of the dike rather than aligning with it. (3) The quantity $E_f \times H$ is greater in the present methodology than in the Shokri and Beyler method (see Fig. 7), yielding a greater net radiation energy release rate per unit length of fire perimeter. Shokri and Beyler recommend a safety factor of 2 be applied to their calculation methodology for design purposes, which in this case would raise the radiation heat flux to a target in the parking lot to 5.8 kW/m^2. The Shokri and Beyler methodology as described in Ref. [3] does not provide a means of evaluating thermal barriers.

[2] The reason for the change in emissive power when evaluating a thermal barrier is discussed at the end of Section 3.1. In brief, measurements of the emissive power of the luminous band surrounding gasoline and diesel fuel fires range from approximately 50 to 100 kW/m^2. The value of 100 kW/m^2 is used in evaluating hazards to nearby structures whereas 50 kW/m^2 is used in evaluating thermal barriers. In each instance, the goal is to err on the conservative side.

6 Conclusion

The methodology for calculating the thermal radiation flux from a large fire on surrounding buildings and people described in this report draws from a substantial amount of research performed in the last quarter century. It is similar in approach to some of the standard methodologies used by fire protection engineers and other safety professionals, but it allows for greater flexibility in handling scenarios that stray from the idealized geometries used in experiments and theoretical analyses. In addition to easy-to-use charts and formulae, the methodology allows for more detailed analysis in cases of increased geometrical complexity.

7 Nomenclature

A	Area of the fire
D	Diameter of the fire
E_f	Emissive power of the flame
F	View factor
H	Flame height
k	Attenuation coefficient for radiative fraction
P	Perimeter length
$\dot{Q}$	Total Heat Release Rate (HRR) of the fire
$\dot{q}''$	Thermal radiation flux
$\dot{q}''_f$	Heat Release Rate (HRR) per unit area of fire
ΔH_c	Heat of Combustion
ΔH_v	Heat of Vaporization
ε_f	Effective emissivity of the flame
χ_r	Radiative fraction of the fire
κ	Attenuation coefficient for emissivity
τ	Atmospheric transmissivity to thermal radiation

8 Conversion Factors

1 m	3.28 ft
1 ft	0.3048 m
1 m^3	264.2 gal
1 kW	3413 Btu/h
1 kW/m^2	317 $Btu/h/ft^2$

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